“Quantum For All”
Q-Lab Town Hall

March 3, 2022

Agenda

- Q-Lab Seed Grant Overview
- Quantum vs. Classical Computing
- Applications & Exemplars
- Resources
- Q&A
National Quantum Laboratory (Q-Lab)

- **Launched in September 2021 in partnership with IonQ**
  - UMD is a world leader in quantum technologies and computing
  - IonQ is a leading developer of quantum computers

- **Focus on developing near-term applications for Noisy, Intermediate-Scale Quantum (NISQ) computers**
  - Finding “killer apps” for QC requires co-development with end-users

- **Q-Lab Partnership Includes:**
  - Enabling broader access to technical expertise and practical QC resources across the UMD ecosystem
  - Access to more powerful QC systems in development than available via cloud providers
  - Co-location of researchers and IonQ to enable collaborative development of applications, to include potential optimization of prototype systems

Q-Lab Seed Grant

- **$300k total**, plus access to Q-Lab time

- **Three Types of Award:**
  - *Exploratory Research* – Engaging non-quantum scientists with QC ($20k)
  - *Proof of Concept* – QIS experts working on NISQ-era applications ($40k)
  - *Curriculum Development* – Supports range of training & education ($10k)

- **Proposals Due:** March 27, 11:59 pm EST
- **Eligibility:** Faculty (TTK & PTK), limited to 1 research & 1 curriculum
- **Quantum Expertise:** Not required for PI. Partnering with a quantum expert is *very strongly encouraged*, but note that seed grant funds must stay inside the university
Q-Lab Seed Grant Process

- Review RFP and apply on UMD’s InfoReady portal

- Required Application Materials
  - Completed Universal Funding Form (50% cost-share)
  - Project Narrative (up to 3 pages + references)
  - Q-Lab Resources Request, if any
  - Budget & Justification
  - Biosketches (up to 2 pages each)

Write for a general audience that might not be familiar with your field of study
Classical computing or quantum computing?

Modern-day digital computers
- extremely powerful
- backbone of the Information Age
- very high precision for arithmetic and algebraic calculations – anything yielding certain outcome
  ... all based on manipulating long strings of '0' and '1' (bits)
- limited when it comes to probabilistic problems:
  - probability distributions not or barely known or are complicated functions
  - data fitting may yield local minima instead of the global minimum
  - large number of parameters often result in exponential growth of complexity
- Random numbers (obtained via mathematical algorithms) are not completely random
  → large samples of random numbers won’t cover the probability space equally
  → cybersecurity keys and encrypted data can – in principle – be decrypted by a third party

Quantum systems
- inherently probabilistic
- populate all possible states simultaneously
- quantum objects superpose (interfere) and can act coherently (entangled)
- number of possible states increases exponentially (2^N for N qubits)

Today's quantum computers
many different implementations!

**Ion-trap Q.C.** (ions placed in quadrupole & oscillating electric field, requires high-vacuum chambers)
- induced excitation of individual atoms (Ytterbium, Barium)
- manipulation by lasers (one for each qubit & one global)
- connectivity: any pair (all-to-all)

- neutral atom traps (trapped in potential wells)
- photonic networks
- quantum dots
  - nanoparticles in 28Si at T=1.0K, spins manipulated by microwaves

**IonQ 2017** 3-qubit Q.C.: 4 laser beams, optical components on 3 levels

**IonQ 2019** 32-qubit Q.C.

**Vacuum chamber (10^{-11} Torr)**

**Ion-trap Q.C. also:** Honeywell, UMD/JQI, U.Innsbruck, ...

**USTC, Shanghai:** 144-modes photon interferometer
Today’s quantum computers (cont.)

Superconducting QC
- Cooper pairs (electron pairs in anharmonic oscillator, operated at T ~15mK)
- Limitations:
  - energy fluctuations at T > 160mK (Cooper pairs unstable)
  - coherence times ~100 μsec
  - place 3 (or 5) qubits together for error correction (only works for uncorrelated Copper pair breaking)
  - connectivity only to nearest neighbors
  - requires many ‘swap gates’

today’s NISQ computers (noisy intermediate-scale quantum era)
- consider the first logic gates and digital computers in 1940s/50s
- better by 2024/5?
  - ion/atom traps: 256 to 512 qubits
  - quantum dots: 64 to 144 qubits
  - superconductors: 512 to 1024 qubits

Basic quantum algorithms

Method:
- access hidden patterns stored in phases and amplitudes of quantum registers via phase manipulations and computing in superposition

Challenges:
- how to get a signal into a quantum register? (initializing input registers)
- how to access the results (“uncomputing” required to disentangle qubit registers)

1) Amplitude Amplification (QAA: generalization of Grover’s algorithm)
- convert phase differences within a quantum register into detectable variations in magnitudes via repeated phase flip & mirror operations
- probabilities fluctuate in QAA iterations → optimal number of iterations
  \[ N_{AA} \approx \frac{2^n}{\sqrt{m}} \]
  (where \(n\) = number of qubits, \(m\) = number of marked (flipped) values)

2) Fourier Transform (QFT: core of many powerful quantum algorithms)
- allows to read out the frequency with which values vary; mirror-image peaks whenever the phase shifts by 180°
  (precision relative to 2^n (where \(n\) = number of qubits))
- more complex signals produce superposition of frequency values → rerun QFT multiple times

3) Phase Estimation: (QPE): returns the superposition of all eigen-phases of an operation \(U\), applies inverse QFT; best results if eigenstates given as input.
- output register contains \(\frac{1}{\sqrt{2^m}} \times 2^m\) (where \(m\) = size of output register) → estimate the eigen-phase \(\phi\) to \(p\) bits precision and probability of error \(\varepsilon\) : size of output reg. \(m = p + \left\lfloor \log(2 + \frac{1}{2\varepsilon}) \right\rfloor\)
Potential applications

Four types of use cases:
1) Quantum simulation of quantum-mechanical systems or processes (Q.C. inherently suited for such intractable quantum simulations).
2) Quantum linear algebra, mostly applied in AI and ML, esp. NLP, but also PDE; mainly hybrid computation: speed-up time-expensive components of conventional methods.
3) Quantum optimization: solve complex problems, esp. discrete optimization, e.g. generative design, traffic management, portfolio optimization, unstructured database searches, improved Monte Carlo simulations
4) Quantum factorization: cybersecurity

Physical qubits needed to achieve 1 logical qubit per technology, based on current error rates for superconducting qubits.
Use cases will combine algorithm archetypes or the archetype is not yet confirmed.
QM: quantum mechanics; MD: molecular dynamics; MM: molecular mechanics.
Absorption, distribution, metabolism, and excretion.

Algorithms and techniques:

a) Quantum Simulation:
- class of procedures that efficiently implement QPU operations for representing Hermitian matrices by breaking down a matrix into a sequence of ‘easier-to-encode’ matrices: \( H = H_1 + H_2 + \cdots + H_n \)
- Variational Quantum Eigensolver (VQE: application of Ritz’ variational theorem)
- applications: quantum physics, quantum chemistry e.g. optimizing catalytic processes: nitrogen fixation, carbon sequestration, protein folding

b) Quantum Annealing:
- find global minimum for combinatorial problems with many shallow local minima
- applications: traveling salesman problem, complex materials/solids, classification problems

c) Quantum Search:
- modified QAA to evaluate boolean sequences (yes/no questions).
- Quantum Approximate Optimization Algorithm (QAOA: yield expectation value from sampling constraint by a cost function)
- applications: search in unstructured databases, combinatorial optimization, oracle functions, boolean satisfiability

d) Quantum Linear Algebra: HHL algorithm (Harrow,Hassidim,Lloyd 2009)
- solve systems of linear equations via eigendecomposition of the coefficients matrix \( A \) amplitude-encoded solution (individual solutions are hidden in amplitudes of the superposition, but derived properties of solution can be extracted: mean, sum, frequency components in solutions, etc)
- applications: computational methods
Algorithms and techniques (cont.):

e) Quantum machine learning (need ~30+ qubits)
- dimensionality reduction: qPCA → find eigendecomposition of the covariance matrix (represented as density operator)
- supervised ML: qSVM → amplitude encoding of hyperplane parameters and least-square optimization
- others (need ~50+ qubits): linear regression, re-enforcement learning, Boltzmann machines, quantum auto-encoder, quantum recommender system, …
- applications: multi-robot path planning, real-time traffic management, autonomous vehicles, finance portfolio & risk management, fraud-prediction modeling, cyber-risk management, …

f) Quantum Image Processing
- analyzing phases in superposition (QAA iterations with inverse QFT)
- applications: supersampling, ray-tracing engines, pixel shader, figure alignment/registration

g) Shor’s factoring algorithm
- determines periodicity of a periodic function for possibly complicated periodicity (hidden subgroup problem) using QFT as coprocessor
- applications: period finding, order finding, discrete logarithms → RSAinteger factorization

Resources:
- UMD quantum initiatives (next slide)

Quantum Initiatives at UMD

- Joint Quantum Institute (jqi.umd.edu), founded in 2006 in partnership with NIST and LPS, is an internationally renowned center for groundbreaking research in quantum science, from theory to experiment.
- Joint Center for Quantum Information and Computer Science (https://quics.umd.edu) is a collaboration with NIST that expands research at the junction of quantum physics, computer science and information theory.
- Quantum Technology Center (qtc.umd.edu) joins researchers in engineering and physics to focus on translating quantum physics into innovative technologies.
- Quantum Materials Center (qmc.umd.edu) explores existing superconductors, as well as the study and creation of quantum materials to enable new devices.
- Institute for Robust Quantum Simulation (rqs.umd.edu) explores the theoretical foundations of quantum algorithms and error correction as well as experimental implementations of quantum simulations.
- LPS Qubit Collaboratory (www.qubitcollaboratory.org), hosted at NSA’s Laboratory for Physical Sciences (LPS) at UMD, pursues collaborative research and innovative workforce development programs.
- Quantum Startup Foundry (quantum.umd.edu/startup) brings together the resources to support entrepreneurs and startups in accelerating the time to bring quantum technologies to market.
- Mid-Atlantic Quantum Alliance (mqa.umd.edu) serves as an inclusive forum to engage and collaborate on research, education, global thought leadership, and building a vibrant and diverse ecosystem to support quantum innovation.
- National Quantum Lab (glue.umd.edu/hpcc/qlab), a new user facility in partnership with IonQ, provides unique research and teaching opportunities using innovative technologies in the field of quantum computing.
- Mid-Atlantic Regional Quantum-Internet (MARQI), a new quantum network enabling quantum computers to communicate over large distances on the internet while preserving quantum coherence (entanglement).
Q-Lab (National Quantum Lab)
User facility of UMD in partnership with IonQ, being established (4505 Campus Drive)

Mission:
• offer training (bootcamps, workshops, classes) in quantum computing
• provide privileged access to IonQ’s trapped-ion quantum computers
• advance research in early applications of quantum computers and quantum networks
• connect researchers from multiple disciplines with interest in these fields
• mentor tomorrow’s experts in quantum computing, its application and technical realization

Questions?
Contact: fklein@umd.edu

Advisory Committee:

Coming soon! (April/May 2022)

• Quantum track on this year’s UMD hackathon!
• Seed Grant program for graduate research

IonQ API tokens limited to active members of the UMCP community; users are not allowed to share IonQ API tokens with anyone outside the UMCP community!
“**Multiverse Computing** today announced a partnership with **IonQ**, the leader in trapped-ion quantum computing, which will **enable financial services organizations to model risk more accurately and quickly** than ever before using the IonQ Quantum Cloud platform within Singularity®, Multiverse’s financial solution.” – Nov 21, 2021

“Rigetti began providing much wider access to its 80-qubit system (Aspen-M), announced a **collaboration with Nasdaq** to develop FS apps. […] The collaboration will focus on ‘machine learning, optimization and simulation problems with Nasdaq’s market perspective, domain expertise and data,’ […] The collaboration will **evaluate financial applications that ‘may benefit from the ability of quantum computing to solve computational problems with improved accuracy, speed, or cost.’” – Feb 17, 2022

“**Quantum-South**’s team has been working in **container load optimization for air cargo since** the **Airbus** Quantum Computing Challenge in 2019 where it became one of the global finalists. Airbus has identified this problem as one of the most challenging in the aerospace industry.” – Feb 14, 2022
“Cambridge Quantum is pleased to announce their collaboration with Roche to design and implement noisy-intermediate-scale-quantum (NISQ) algorithms for early-stage drug discovery and development.” – Jan 29, 2021

SEEQC, the Digital Quantum Computing company, today announced its UK-based team has been awarded a £6.85M grant from Innovate UK to build a commercially scalable application-specific quantum computer designed to tackle prohibitively high costs within pharmaceutical drug development. – Nov 5, 2021

1. Sensor positions for automated driving functions: Accenture’s winning team tackled the problem of optimising the positioning of sensors for highly automated driving functions.

2. Simulation of material deformations: The jury concluded that the quantum computing start-up Qu&Co stood out with its approach to solving partial differential equations in the field of numerical simulation.

3. Configuration optimisation of pre-series vehicles: The winning team from 1QBit and NTT came out on top with hybrid algorithms for solving satisfiability problems in propositional logic for optimising equipment configuration.

4. Automated quality analyses: The QC Ware team stood out with its approach, drawn from the field of machine learning, that can be used in image recognition in the area of quality analysis.
QSF TraQtion

• Collaborations in the areas of distribution loading, QAOA, QML, Quantum Monte Carlo
• Working with professors/their PhD students on algorithm development for financial and actuarial use cases.

CLASSIQ

• Collaborations to automatically synthesize high-level models into optimized quantum circuits

QUANTUM FLYTRAP

• Collaborations to make quantum computing applications more accessible through better user interface design